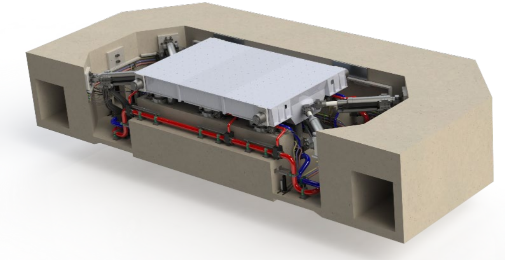

SimCenter Tools and Capabilities for Experimental Researchers

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Sang-ri Yi
Software Developer

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Acknowledgments

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PURDUE UNIVERSITY
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NSF Award #2129782
SimCenter
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SimCenter
Computational Modeling and Simulation
NSF Award #2131111
UNIVERSITY OF COLORADO BOULDER
CONVERGE
Social Science/Interdisciplinary Resources
NSF Award #1841338
UNIVERSITY OF WASHINGTON
Natural Hazard
Reconnaissance (RAPID) Facility
NSF Award #2130997
UNIVERSITY OF TEXAS, AUSTIN
DesignSafe
Community Cyberinfrastructure
NSF Award #2022469
DesignSafe
OREGON STATE UNIVERSITY
Large Wave Flume and
Directional Wave Basin
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Natural Hazards
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Research
Infrastructure
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Hybrid Simulation Testing
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Geotechnical Centrifuges
NSF Award #2037883
FLORIDA INTERNATIONAL UNIVERSITY
Wind Simulation
NSF Award #2037899
UNIVERSITY OF CALIFORNIA, SAN DIEGO
Large High-Performance Outdoor Shaker Table
NSF Award #1520904
LHPOST
NICHE
NICHE
Planning for the new, shared-used National
Full-Scale Testing infrastructure for Community Hardening
in Extreme Wind, Wave and Surge Events
NSF Award #2131961

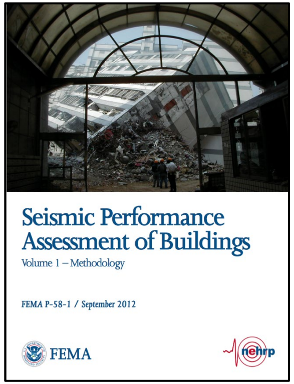
SimCenter's Mandate

Advance the Nation's capability to **simulate the impact** of natural hazard events on structures, lifelines, and communities.

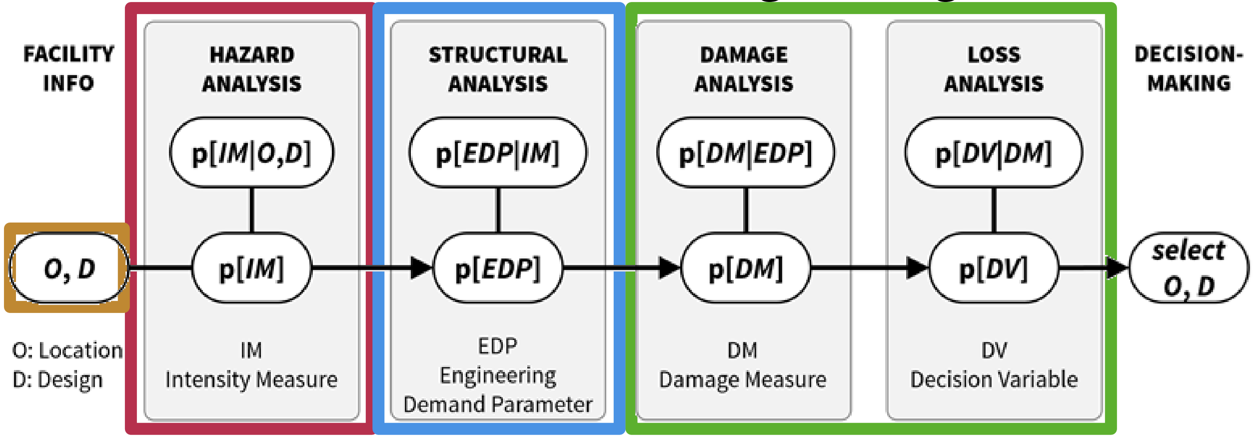
Create an open-source and extensible application framework, integrate existing tools and data, and develop new software to provide the **next-generation of regional disaster simulation tools**

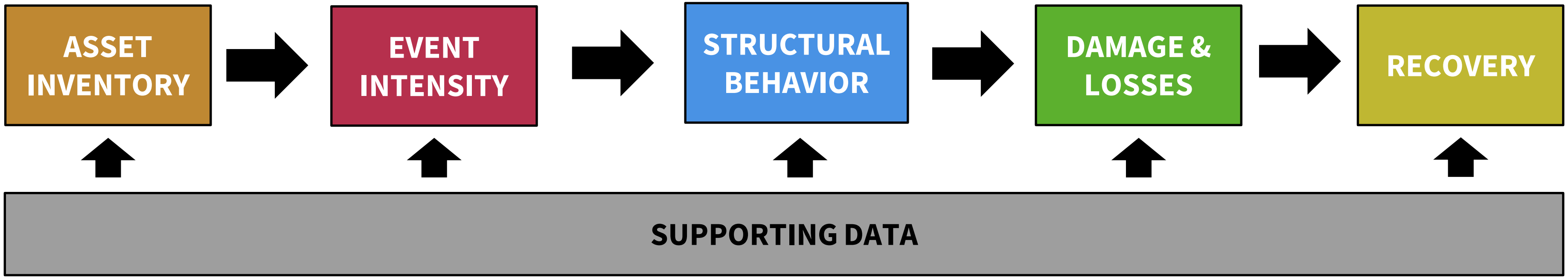
Support researchers and practitioners with **education and training**, and connect them with high-performance computing resources.

Unifying Simulation Platform



Performance-Based Engineering





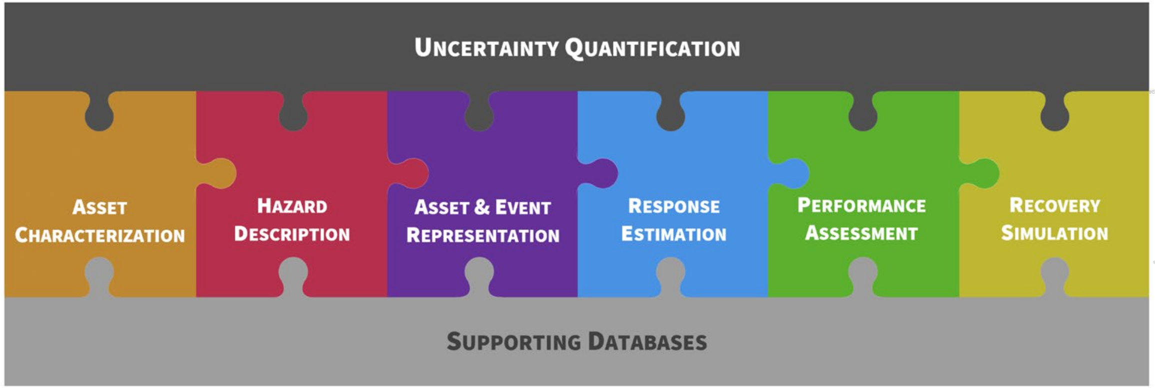
Unifying Simulation Platform

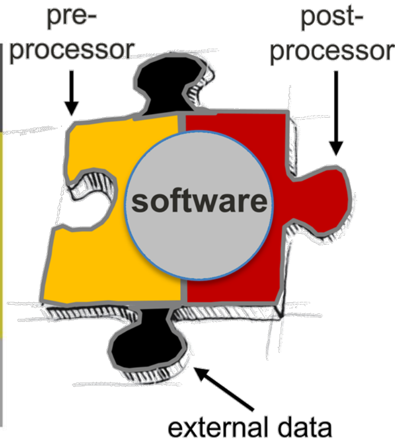
SimCenter Application Framework

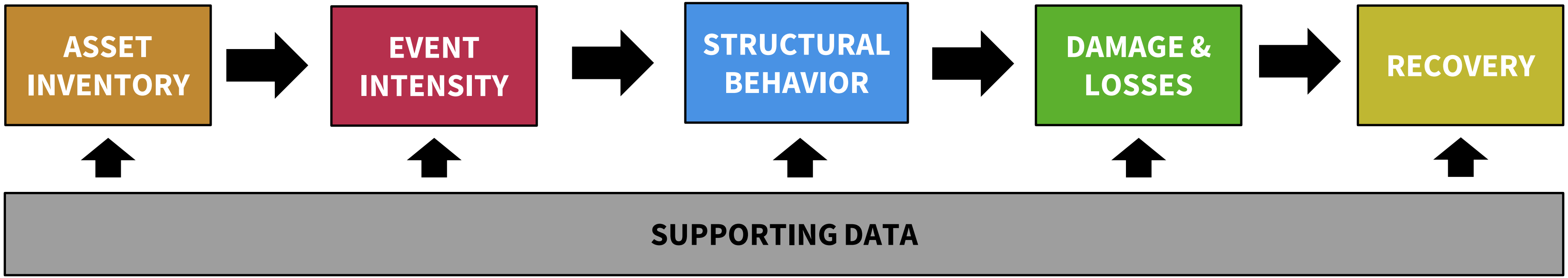
Open Source

Multi-Fidelity

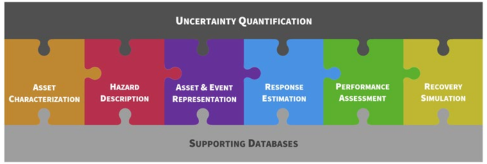
Multi-Hazard

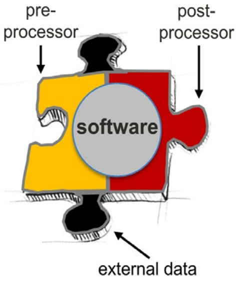






Unifying Simulation Platform



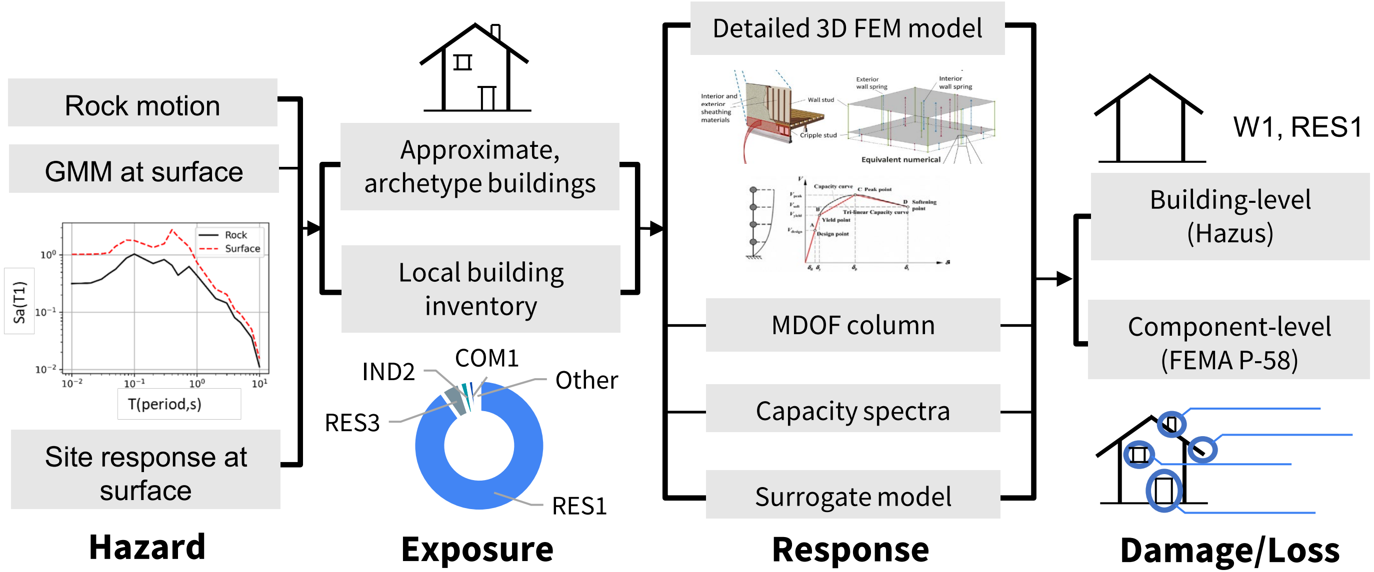


Open Source

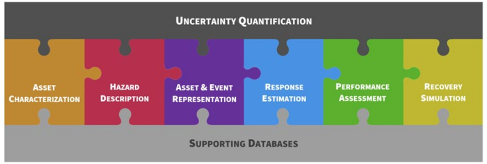
Multi-Fidelity

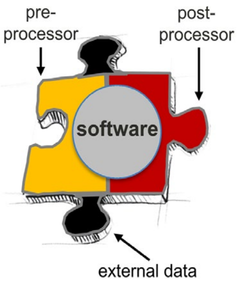
Multi-Hazard

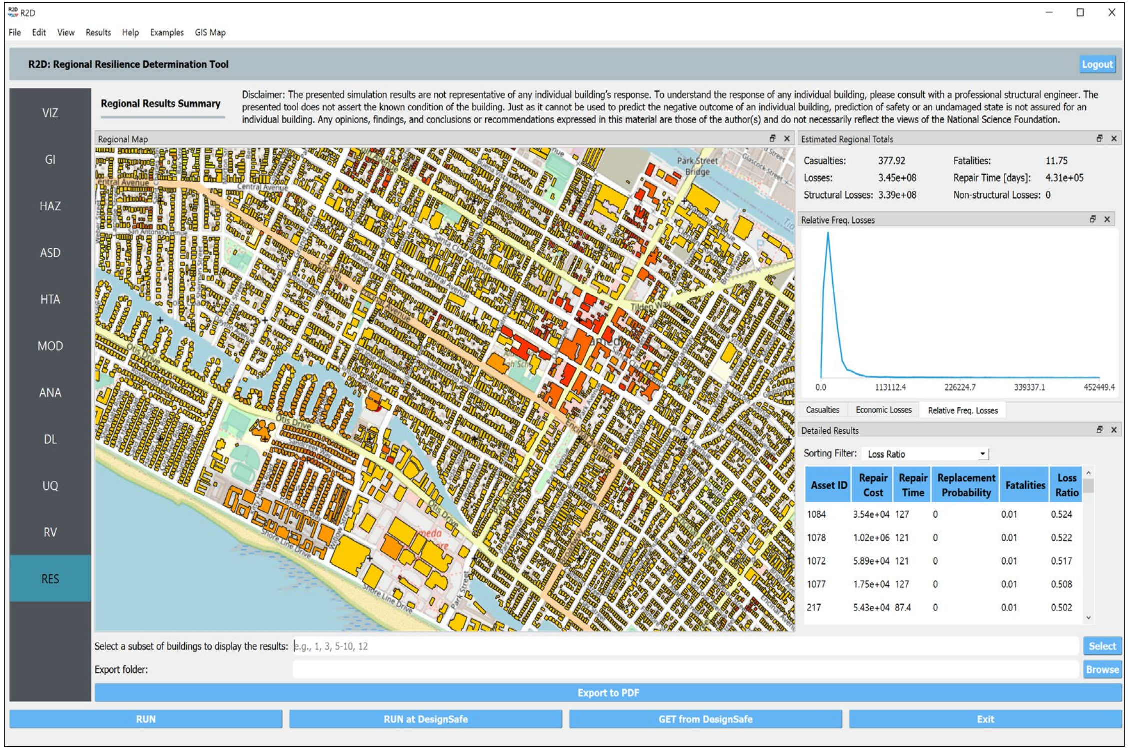
Example Workflows – Earthquake Risk



Desktop Applications





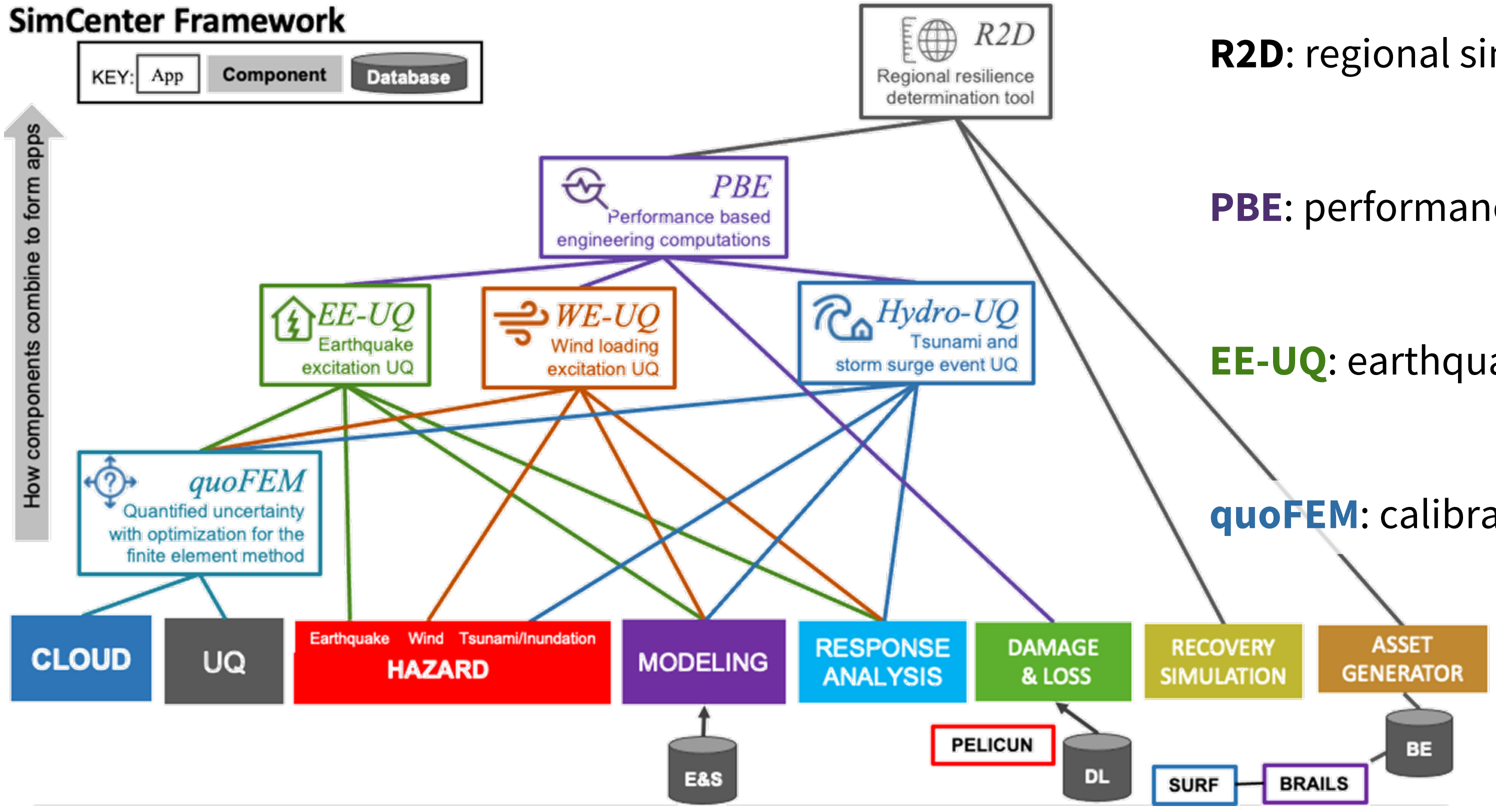


Open Source

Multi-Fidelity

Multi-Hazard

Desktop Applications



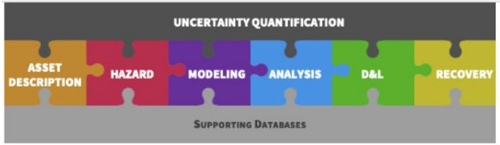
R2D: regional simulation

PBE: performance assessment

EE-UQ: earthquake response

quoFEM: calibration

R2D – Regional Simulation



Create and run complex workflows for regional simulation of natural hazards to facilitate research in disaster risk management and recovery.

Asset definition

- CSV and GIS files

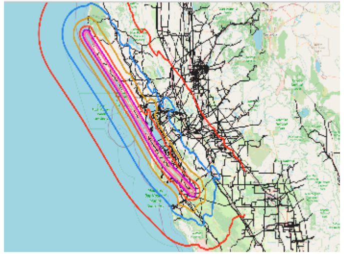
Hazard definition

- Regional Site Response
- Custom earthquake and hurricane grids
- Earthquake, hurricane, tsunami rasters
- Earthquake, hurricane event simulation

Response, Damage and loss

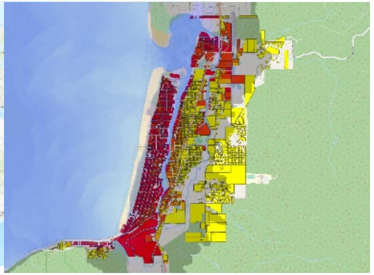
- FEM simulations of response
- HAZUS and other fragility models
- User-provided fragility functions

Multiple Hazard Types



Earthquakes

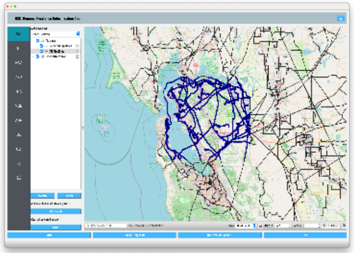
Hurricanes



Tsunamis

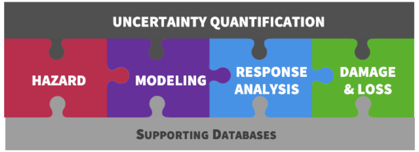
Multiple Asset Types

Buildings



Lifelines

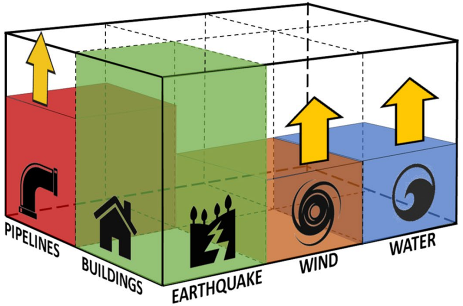
PBE – Performance Assessment

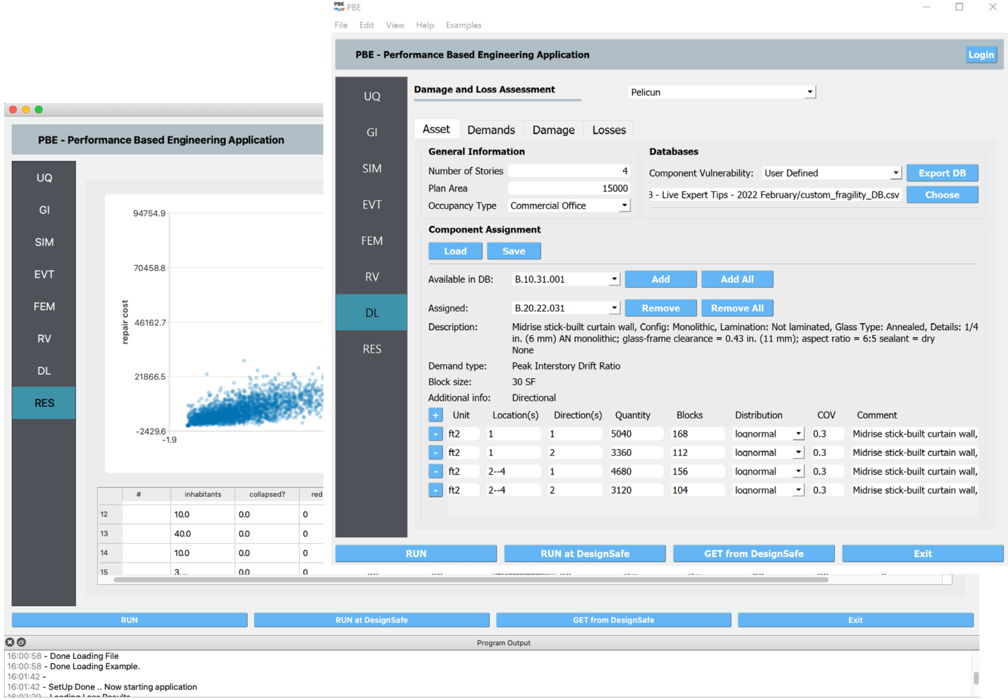


Integrates UQ applications of quoFEM, Building Model Generators, Earthquake Loading, analysis engine and our PELICUN tool for damage and loss assessment.

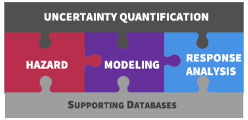
Damage & Loss (using PELICUN):

- Building-level assessment (e.g., HAZUS)
- Component-level assessment (e.g., FEMA P58)
- Supports external response estimation
- Customizable fragility & consequence functions





EE-UQ – Earthquake Engineering



EE-UQ V3.0

- Earthquake Simulation of Buildings and Site Effects
- Automatic model generators and surrogate model development

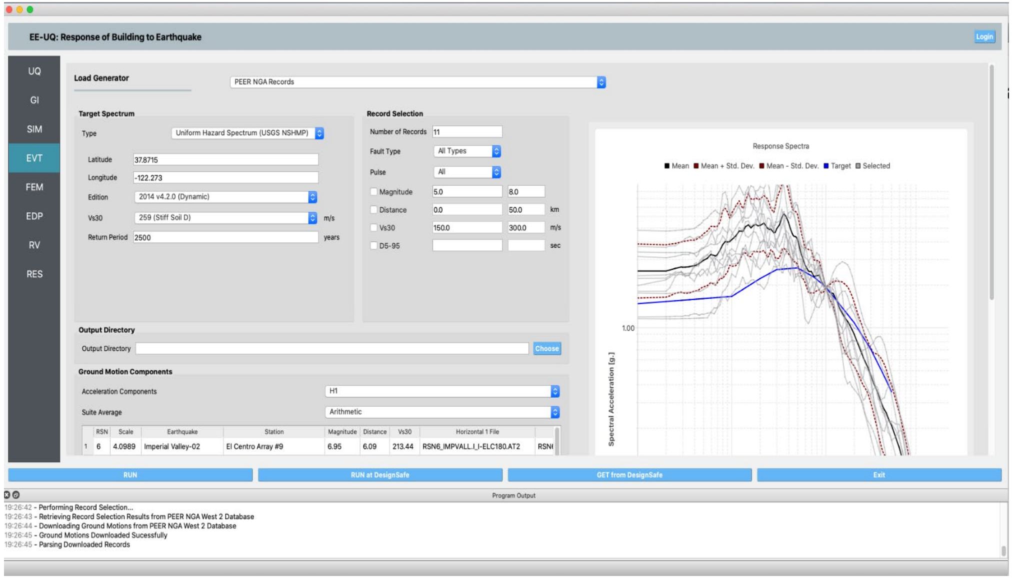
Hazard (Earthquake):

Target Spectrum (OpenSHA, OpenQuake)

Ground Motion Selection/Scaling (PEER NGA)

Stochastic Motions

Site Response with Random Fields



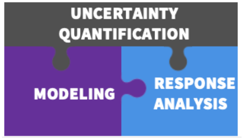
Structural Modeling:

Detailed FE Models (OpenSees)

Simplified Nonlinear Model

Auto Steel and RC Building Design

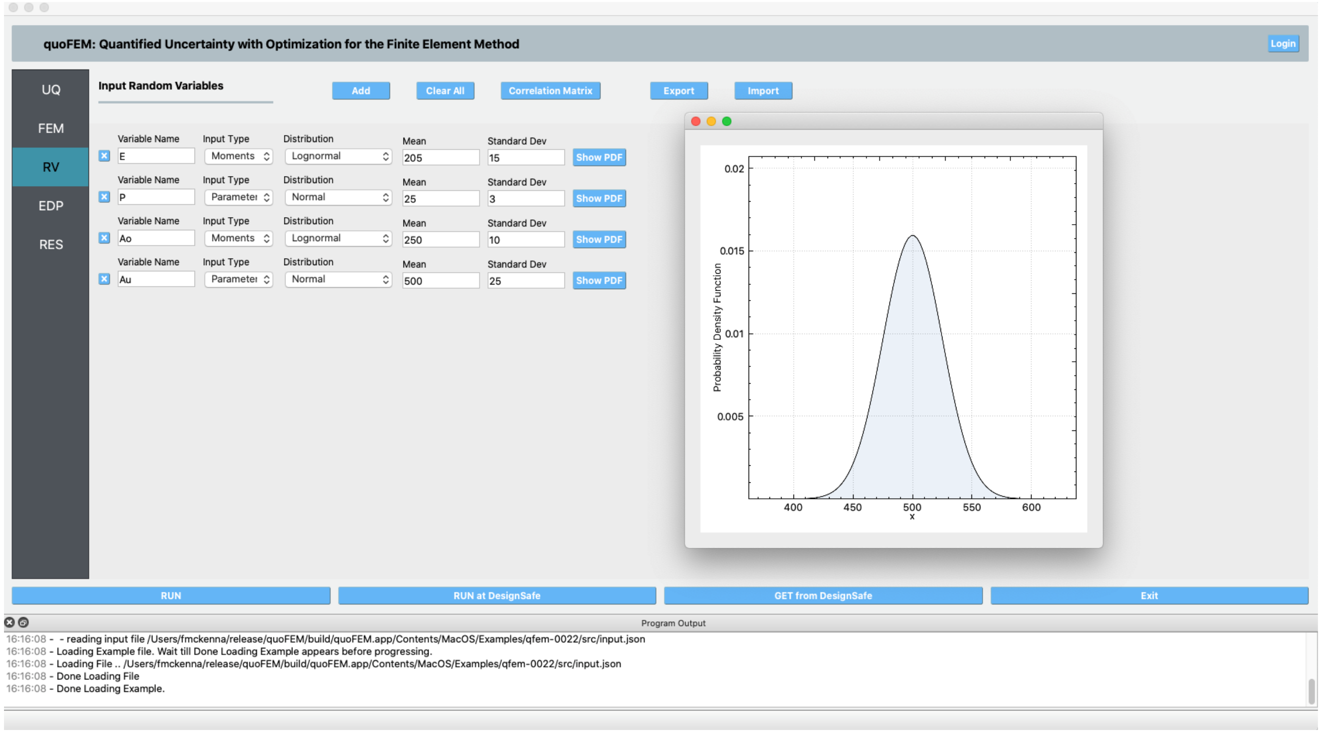
quoFEM – Calibration



Integrates Simulation Applications with UQ Applications

UQ Problem Types

- Sampling
- Sensitivity
- Reliability
- Calibration
- Bayesian Calibration
- Surrogate Modeling



Broadening Impact

The SimCenter ecosystem facilitates collaboration and accelerates dissemination of new ideas.

Examples:

- 40 tall steel building models – published in DesignSafe soon
- Automatic model generator for steel and RC frames (AutoSDA & RC-FIAP)
- Idealized shear column model for buildings (MDOF-LU)

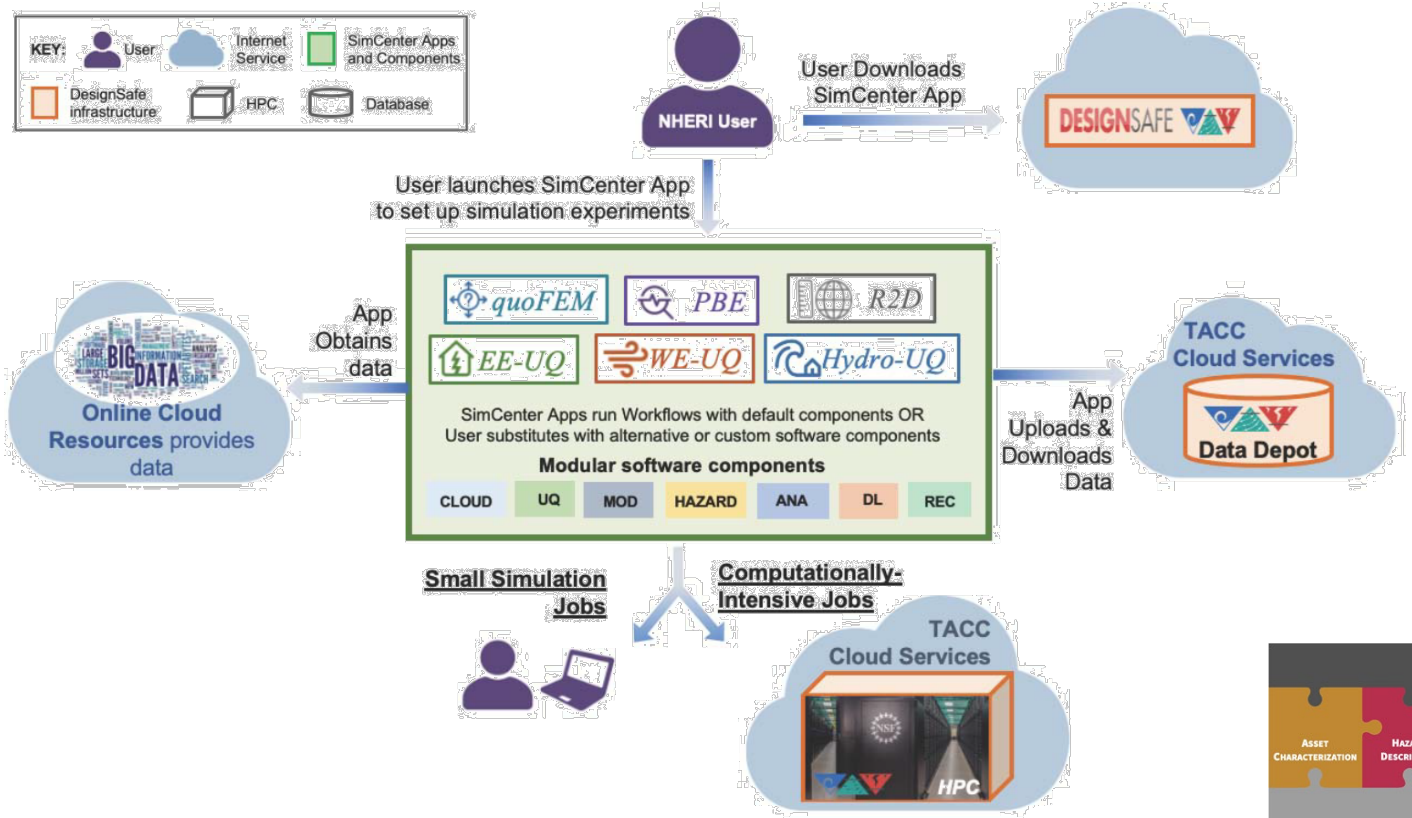
Enhancing Intellectual Merit

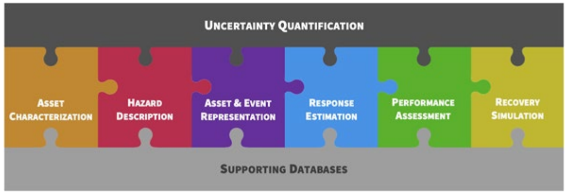
Leverage advanced methods developed in the community

Examples:

- Complex, hazard-consistent ground motion record selection
- Surrogate modeling techniques for structural response estimation
- Performance assessment methods to estimate damage & losses
- **Sang-ri shows additional examples later**

Connections to Other Resources





Multi-Disciplinary Collaboration

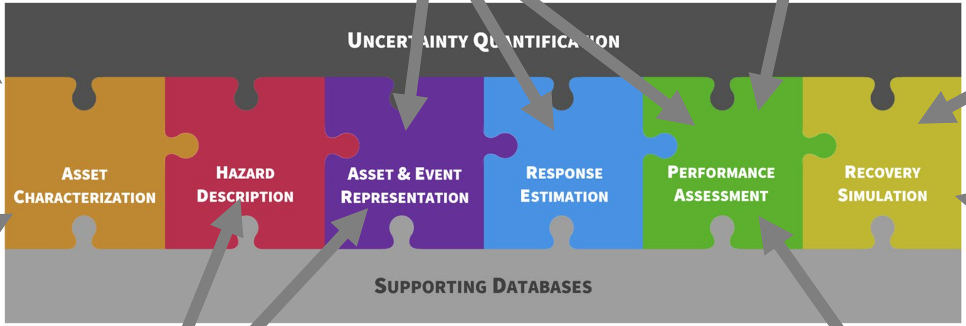
Hi-Fidelity Asset Simulations

Multi-Hazard Component Damage Models

Urban Planning and Growth

Recovery Modeling

Policy Interventions



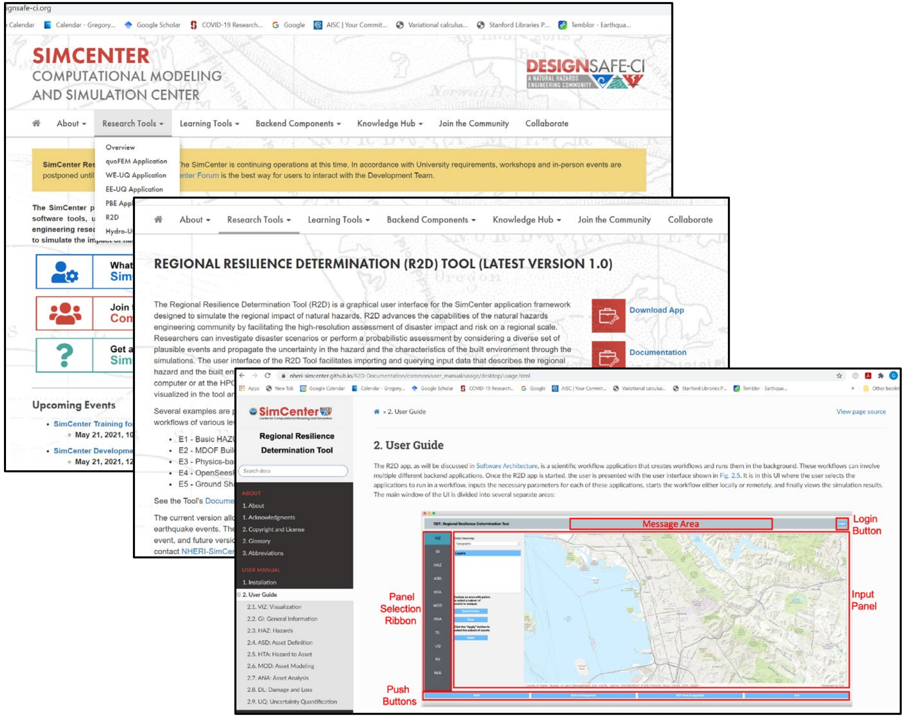
Socio-Economic Implications

Changing Demographics

Hazard Simulations

Environmental and Ecological Impacts

Trainings & Resources



SimCenter Website

- Software & Documentation
- Upcoming Education & Training Events
- Forum & Other Communication
- Visiting Researcher Position
- REU Positions

https://simcenter.designsafe-ci.org/

About quoFEM

Quantified Uncertainty and Optimization for the Finite Element Method (quoFEM)

Forward propagation

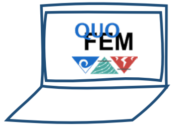
Sensitivity analysis

Reliability analysis

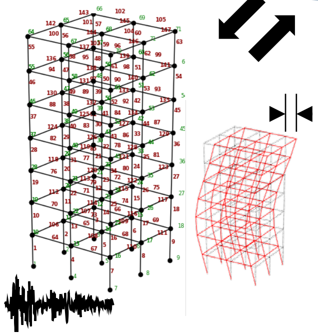
Surrogate modeling/ Reducedorder modeling

Bayesian calibration

Deterministic calibration



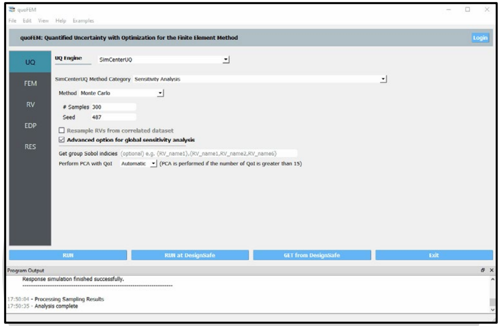
Simulation model



(OpenSeespy user manual - Upadhyay)

experimental data

Benefits – SimCenter Tools for Experimental Researchers




```
Instead of                  use
      set E 205                   pset E 205
      set P 25                    pset P 25
      set Au 500                  pset Au 500
      set Ao 250                  pset Ao 250
```

Easy-to-use user interface

Link with the DesignSafe HPC

1. **Moderate-to-high dimension**
2. **Efficient algorithms** for expensive models
3. **Advanced Calibration and UQ techniques**
   - Model class selection
   - Hierarchical Bayesian
   - Surrogate-enabled calibration

Accelerated and advanced algorithms

Inside quoFEM

FEM Engine	→	UQ Method
OpenSees		Sampling
Python		Global Sensitivity
FEAPpv		Reliability
Custom		Deterministic Calibration
Surrogate Model		Bayesian Calibration
		Surrogate Modeling
		Custom UQ

UQ Algorithms

- Latin Hypercube Sampling/Monte Carlo
- Gaussian Process Regression
- Polynomial Chaos Expansion

- Probability model-based GSA (PSA)
- Principal component analysis-based PSA
- Smart Monte Carlo Method

- Local Reliability (FORM, SORM, etc.)
- Global Reliability
- Importance Sampling

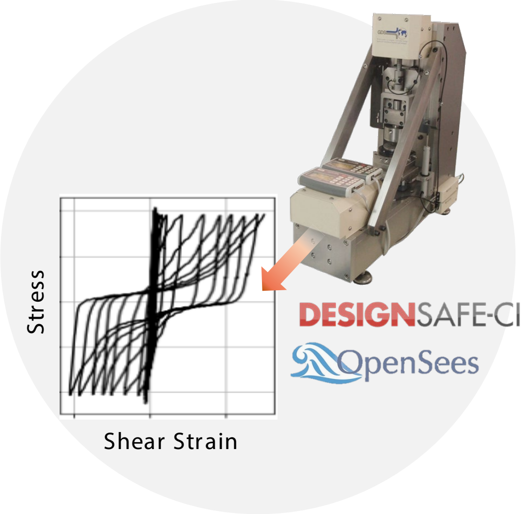
- OPT++ GaussNewton
- NL2SOL
- Gradient-free

- Transitional Markov Chain Monte Carlo
- Differential Evolution Adaptive Metropolis

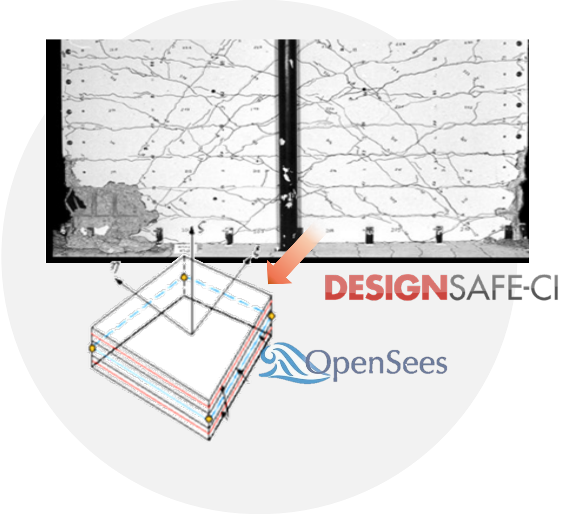
- Gaussian Process (GP) Surrogate Modeling
- Adaptive Design of Experiments
- Non-homogeneous GP modeling
- Multi-fidelity GP Modeling
- Probabilistic Learning on Manifold (PLoM)

- User-provided Algorithms

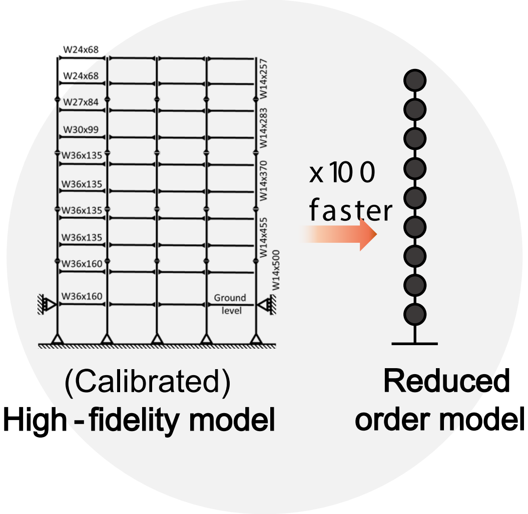
Examples



Soil Material Model Calibration



RC Shear Wall Calibration



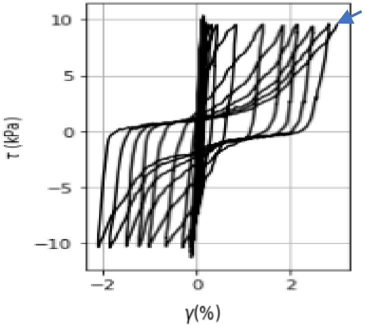
Reduced Order Modeling of High-fidelity Building Model

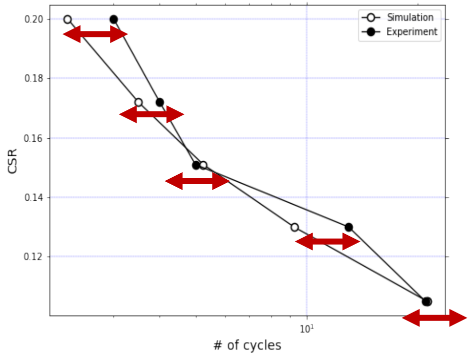
Adithya Nair
2021summer REU from the Ohio State University
Currently grad. student at UC Berkeley

Ex1. Constitutive soil model calib.

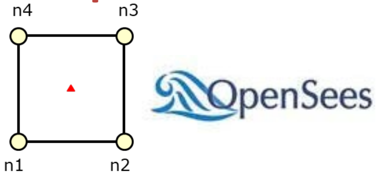
- To calibrate **liquefaction capable soil material model** (**PM4Sand**) **(Boulanger and Ziotopoulou, 2017)**
- Experimental output - Number of cycles to onset of liquefaction at given cyclic stress ratios (CSR)

Experimental data

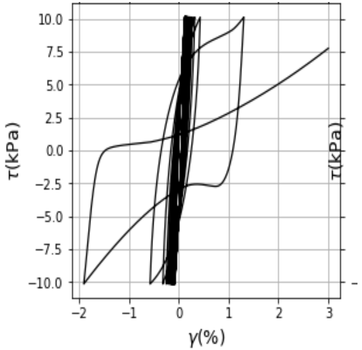




Computational model



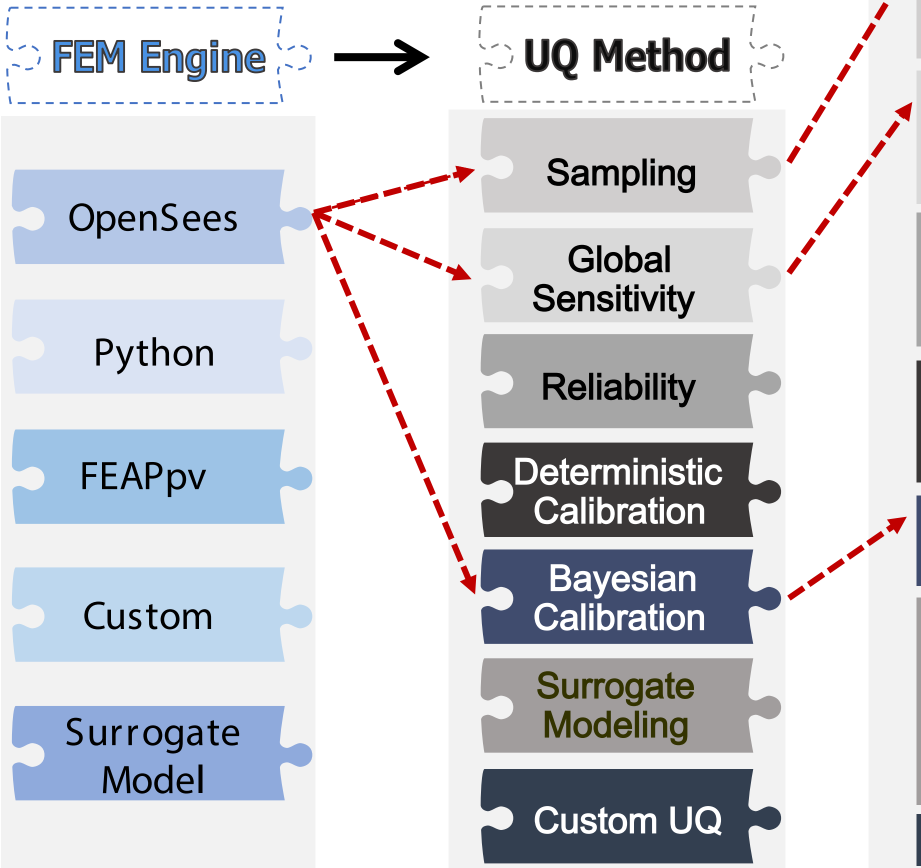
Material: PM4Sand v3
Element: SSPquad (4 node)
Number of Parameters: 25
(Chen and Arduino, 2021)



Questions.

1. What are the **important** parameters?
2. What are **optimal** parameter values?
3. How the **uncertainty in the parameters** affect lateral spreading response?

Inside quoFEM



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- Gaussian Process Regression
- Polynomial Chaos Expansion

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- Smart Monte Carlo Method

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- Gaussian Process (GP) Surrogate Modeling
- Adaptive Design of Experiments
- Non-homogeneous GP modeling
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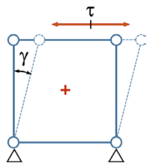
- Probabilistic Learning on Manifold (PLoM)

- User-provided Algorithms

Global Sensitivity Analysis

- What are the important parameters?
- Method: Probabilistic model based global sensitivity analysis (Hu and Mahadevan 2019)

Computational model



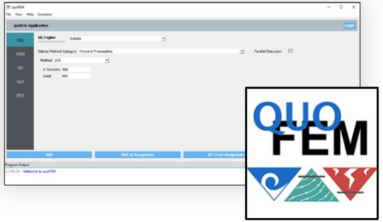
Material: PM4Sand v3
Element: SSPquad (4 node)

D_r : relative density
G_o: shear modulus coefficient
h_{po}: contraction rate parameter

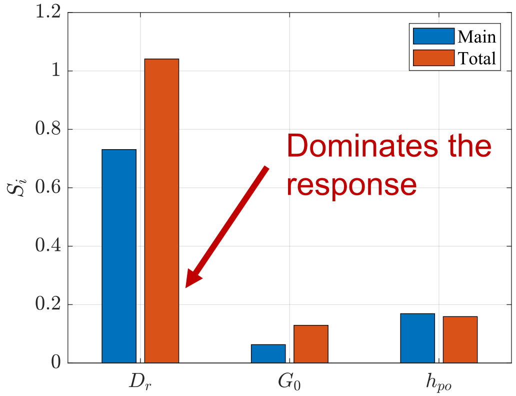
OpenSees

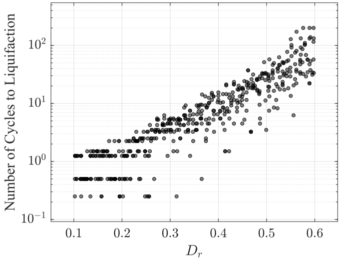
Opensees Script

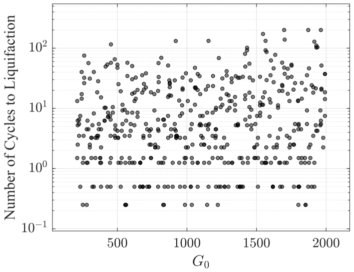
```
# Create material
#           PM4Sand  tag    Dr    G0    hpo    den   Patm  h0    emax   emin   nb   nd   Ado    zmax
nDMaterial PM4Sand   1     $Dr   $G0   $hpo   $rho $Patm $h0   $emax $emin   $nb  $nd $Ado   $zmax

# Create element
element SSPquad   1     1 2 3 4    1  "PlaneStrain" 1.0

# Create analysis
constraints Transformation
test        NormDispIncr 1.0e-5 35 1
algorithm   Newton
numberer    RCM
system      FullGeneral
integrator  Newmark [expr 5.0 / 6.0] [expr  4.0 / 9.0]
rayleigh    $a0 $a1 0.0 0.0
analysis    Transient

# Apply consolidation pressure
set pNode [expr $sigvo / 2.0]
pattern Plain 1 {Series -time {0 100 1e10} -values {0 1 1} -factor 1} {
    load 3  0.0  $pNode
    load 4  0.0  $pNode
}
updateMaterialStage -material 1 -stage 0

analyze 100 1
set vDisp [nodeDisp 3 2]
set ts1 "{Series -time {100 80000 1.0e10} -values {1.0 1.0 1.0} -factor 1}"
eval "pattern Plain 2 $ts1 {
    sp 3 2 $vDisp
    sp 4 2 $vDisp
}"
```



Sensitivity indices





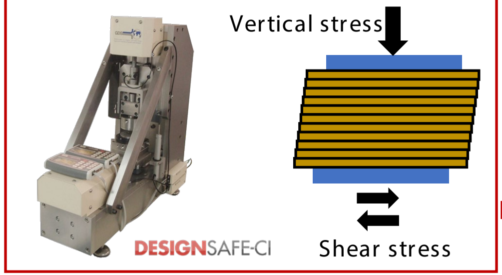


Nair AS et al. (2021), Research Experience for Undergraduates (REU), Uncertainty Analysis of Seismic Soil Liquefaction using quoFEM. DesignSafe-CI.
Yi, S. et al (2022), Sensitivity analysis and Bayesian calibration of a constitutive soil model using quoFEM, OpenSees Days 2022 Eurasia, July 7-8, Turin, Italy

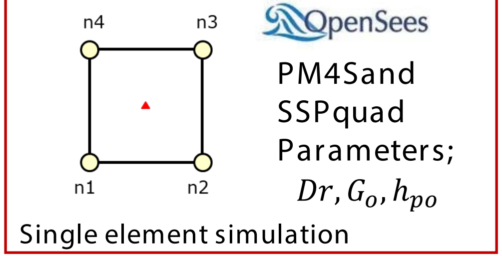
Bayesian Parameter Calibration

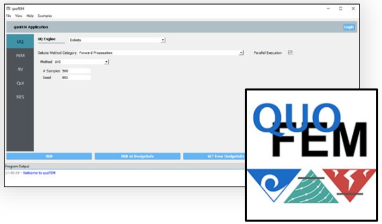
- What are the parameter values?
- Method: Transitional Markov Chain Monte Carlo (Ching and Chen, 2007)

Experimental data

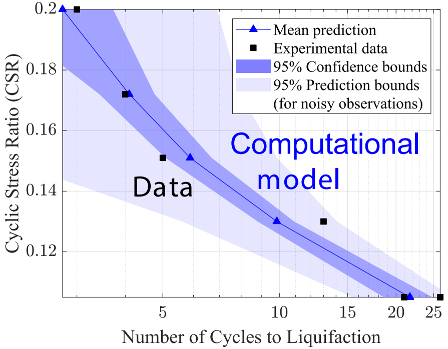


Computational model

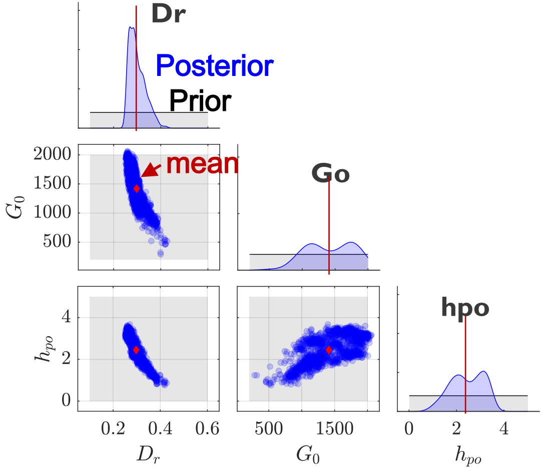




Calibrated output



Predictions from calibrated model

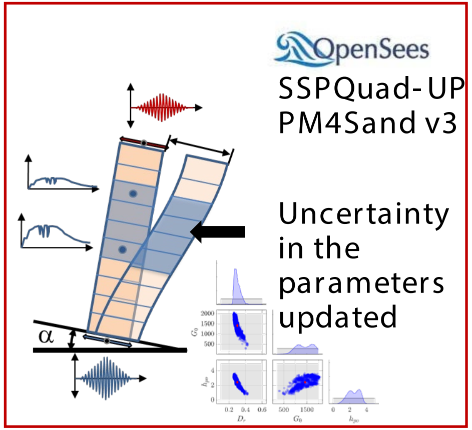


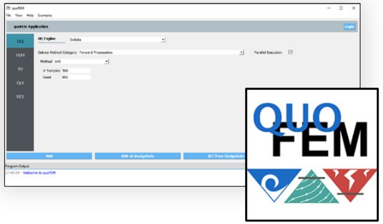
Nair AS et al. (2021), Research Experience for Undergraduates (REU), Uncertainty Analysis of Seismic Soil Liquefaction using quoFEM. DesignSafe-CI.
Yi, S. et al (2022), Sensitivity analysis and Bayesian calibration of a constitutive soil model using quoFEM, OpenSees Days 2022 Eurasia, July 7-8, Turin, Italy

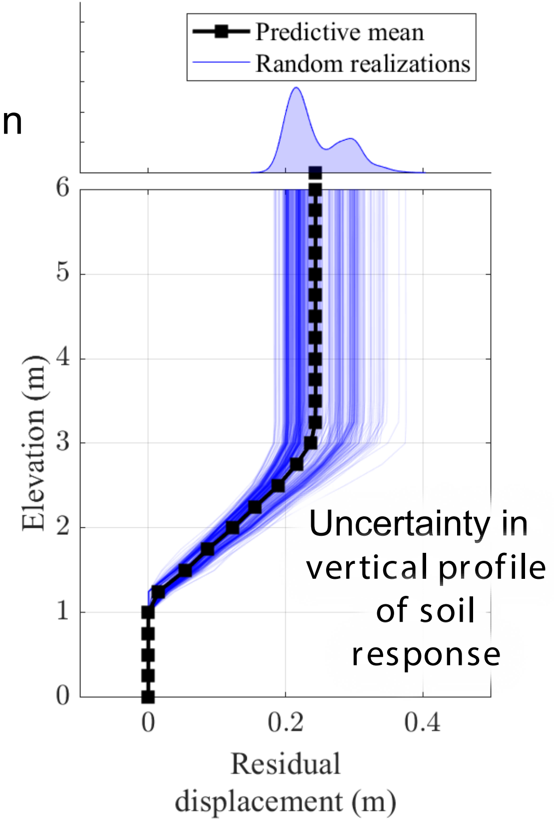
Forward Uncertainty Propagation

- Random variables: Dr, G_o, h_{po}
- Output: Vertical profile of horizontal displacement of the soil column

Computational model







Nair AS et al. (2021), Research Experience for Undergraduates (REU), Uncertainty Analysis of Seismic Soil Liquefaction using quoFEM. DesignSafe-CI.
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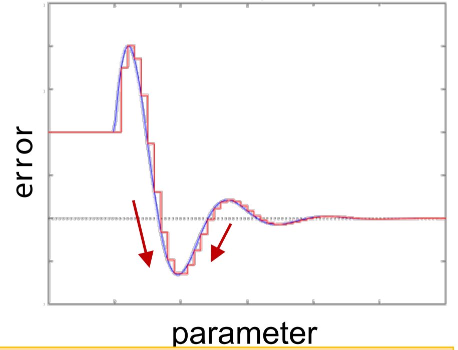
Ex2. Calibration of RC wall properties

(Stokley and Lowes, 2022)

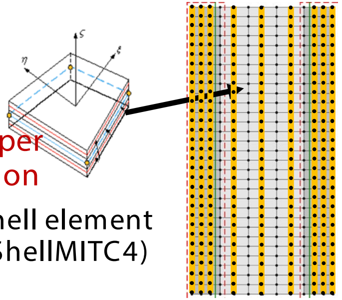


Calibrating material model parameters using “structural” response

Experimental data

Cyclic load test data on
142 reinforced concrete walls
(Shegay et al. 2021)

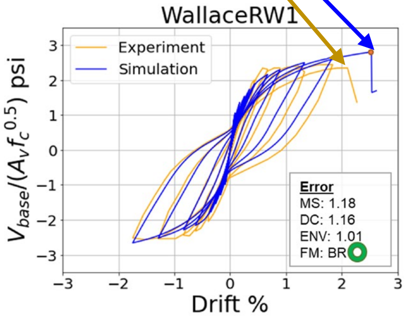
Computational model



3 hours per simulation

shell element (ShellMITC4)

To match deformation capacity



Challenges.

1. Computationally expensive model
2. Gradient-based algorithms not applicable

Parameters of interest

- **Concrete** crushing energy (Gfcc/Gfuc) **→ Concrete compression failure**
- **Steel** rupture strain reduction factor (SRS) **→ Rebar rupture**

Inside quoFEM

FEM Engine → **UQ Method**

FEM Engine
- OpenSees
- Python
- FEAPpv
- Custom
- Surrogate Model

UQ Method
- Sampling
- Global Sensitivity
- Reliability
- Deterministic Calibration
- Bayesian Calibration
- Surrogate Modeling
- Custom UQ

UQ Algorithms

- Latin Hypercube Sampling/Monte Carlo
- Gaussian Process Regression
- Polynomial Chaos Expansion

- Probability model-based GSA (PSA)
- Principal component analysis-based PSA
- Smart Monte Carlo Method

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- Global Reliability
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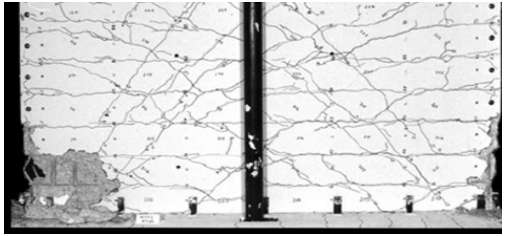
- User-provided Algorithms

Ex2. Calibration of RC wall properties (Stokley and Lowes, 2022)

Experimental data

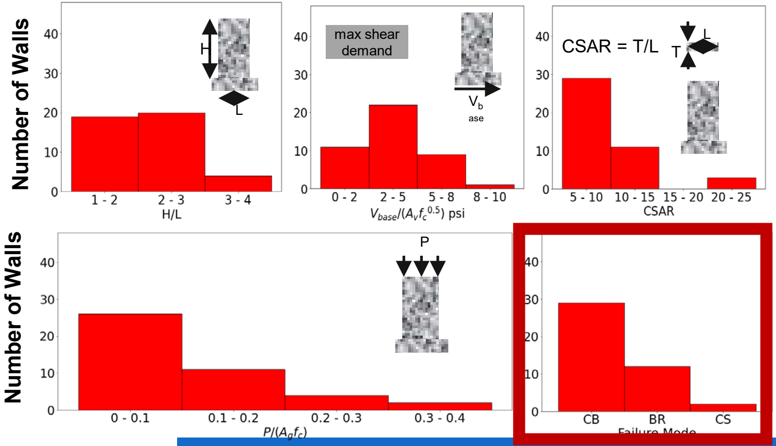


DESIGNSAFE-CI

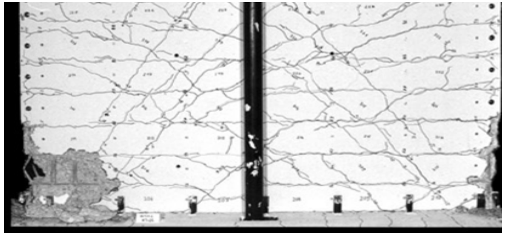
Data Depot Project 2430
(Shegay et al. 2021)

142 walls from 32 research programs
mostly rectangular walls tested under
cyclic protocols in 1960-2010s

Summary

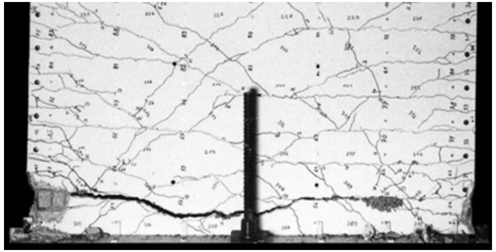


Failure Mode CB
Compression Buckling



Compression - buckling failure (Dazio et al. 2009)

Failure Mode BR
Bar Rupture

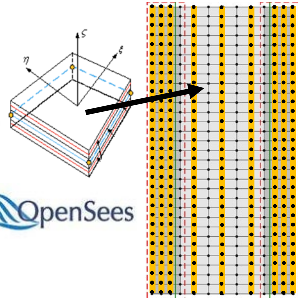


Tension failure (Dazio et al. 2009)

Failure Mode CS
Compression Shear

Ex2. Calibration of RC wall properties (Stokley and Lowes, 2022)

Computational model



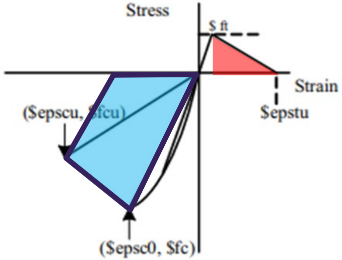
Multi-layer shell element (ShellMITC4)

Parameters of interest

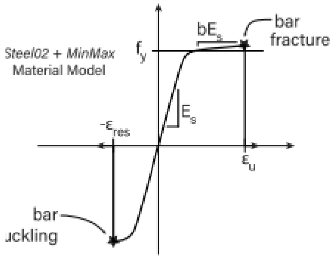
- **Concrete** crushing energy (Gfcc/Gfuc)
  - crushing failure mode
- **Steel** rupture strain reduction factor (SRS)
  - bar fracture failure mode

Concrete

(PlaneStressUserMaterial)



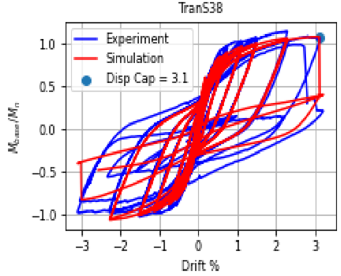
Steel02

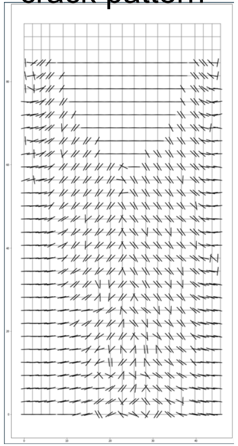


Simulated concrete crack pattern

Failure Mode CB

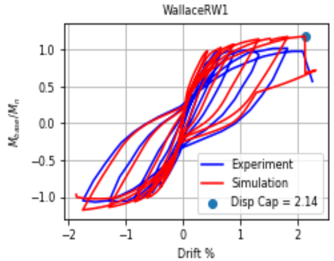
Compression Buckling

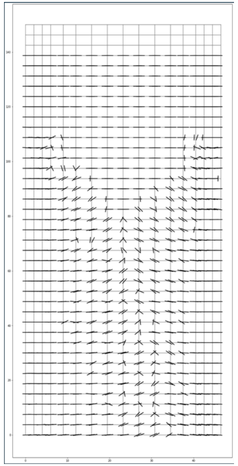




Failure Mode BR

Bar Rupture





Failure Mode CS

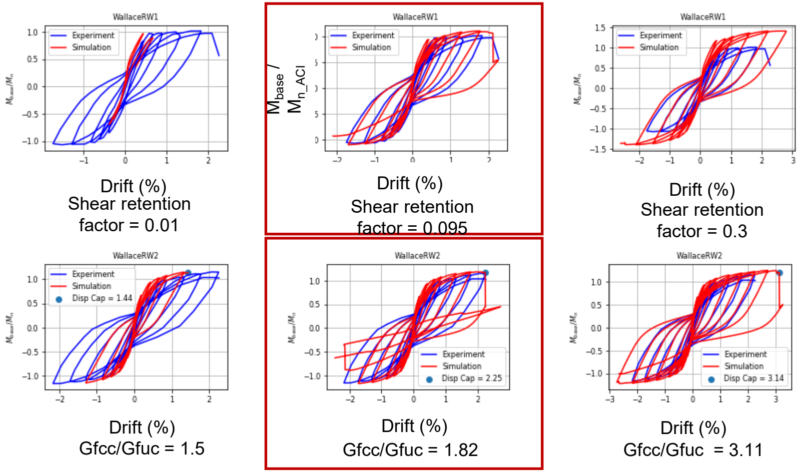
Compression Shear

Stokley, J., Lowes, L., 2022, Modeling reinforced concrete walls with shell elements to simulate through opensees and using jupyter to post process results, Design-Safe Jupyter notebook

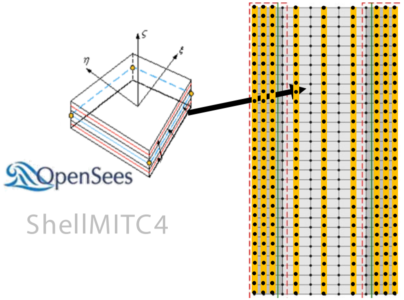
Forward Propagation

Enabled by DesignSafe

Parametric study



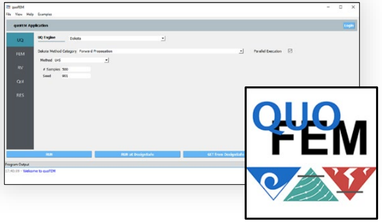
Computational model

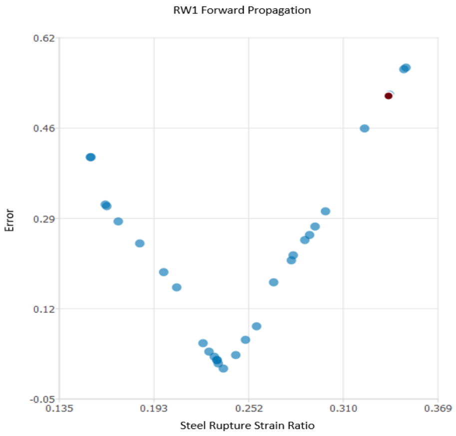


cyclic response of flexure-controlled wall model

3 hours each

DESIGNSAFE-CI



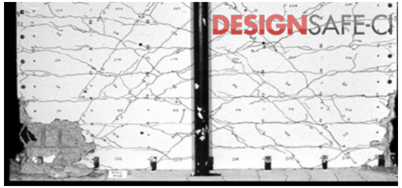


Automated Calibration

Method: pattern search

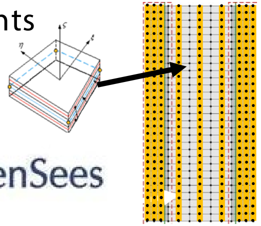
Experimental data

Rectangular walls
under cyclic loading



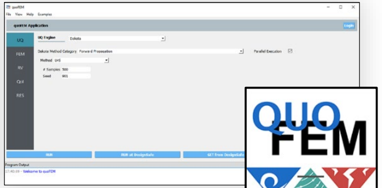
Computational model

Reinforced Concrete
Walls with Shell
Elements



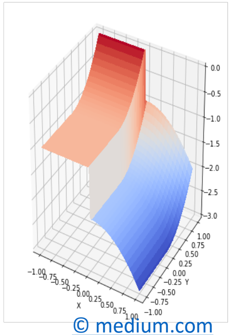
OpenSees

Gradient-free algorithm

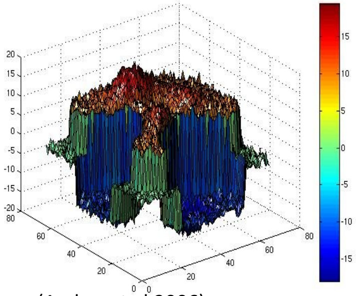


QUO FEM

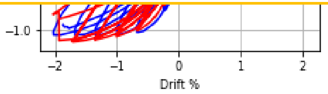
When response function is like..



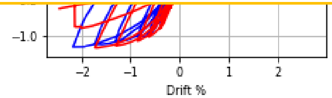
© medium.com



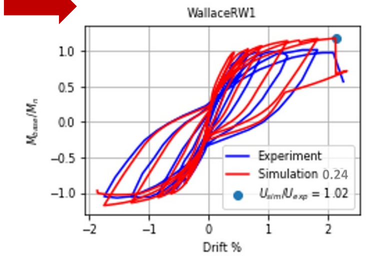
(Ascher et al.2006)



SRS* = 0.315

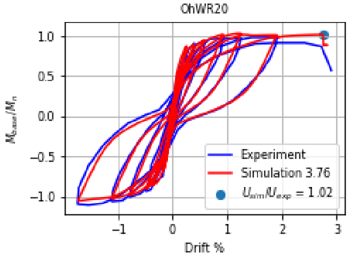


Crushing Energy Ratio = 1.81



SRS = 0.238

Bar buckling



Crushing Energy Ratio = 3.76

Concrete Crush

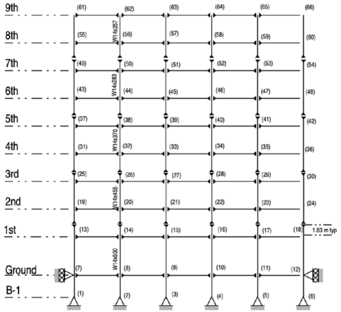
*SRS: Steel Rupture Strain Ratio

Ex3. Reduced Order Modeling

Physical experiment

quoFEM calibration

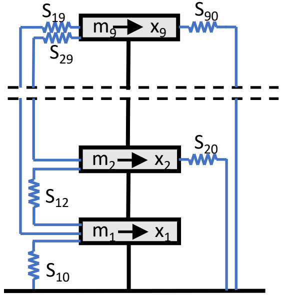
High fidelity model



minutes~hours

quoFEM calibration

Reduced order model



seconds~minutes

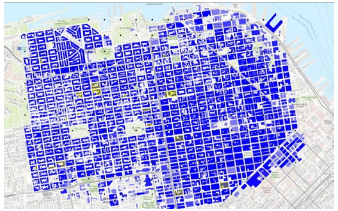
R2D

EE-UQ

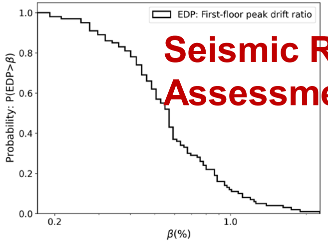
quoFEM

forward uncertainty propagation

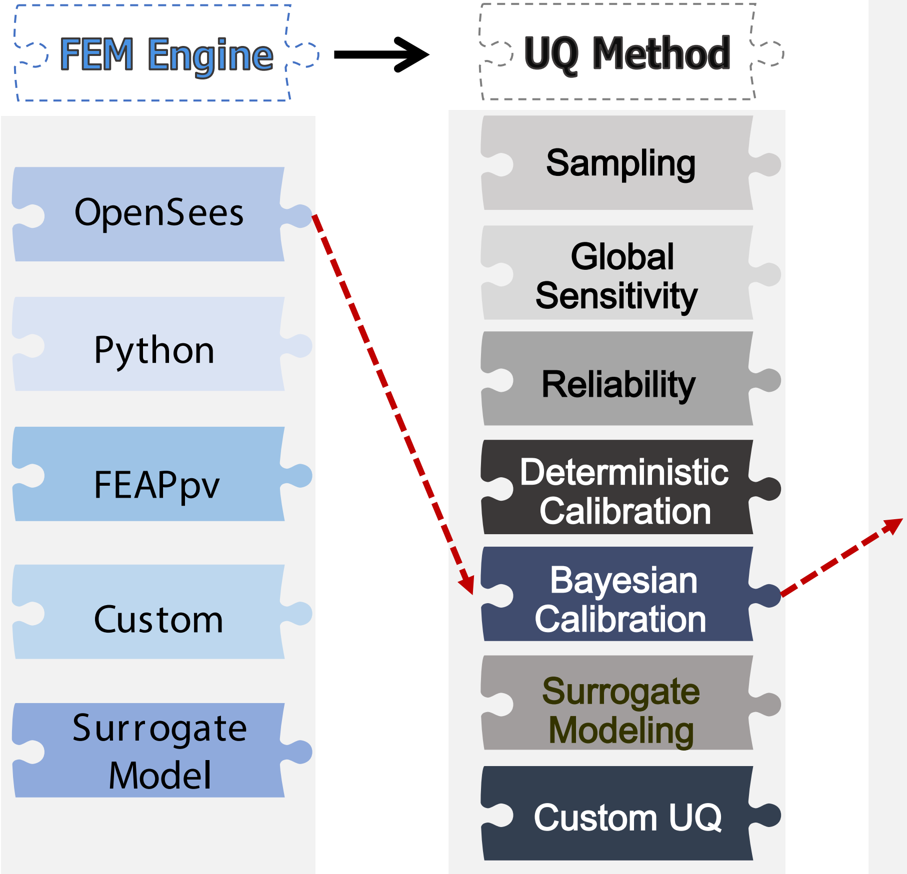
Regional Performance Assessment



Seismic Risk Assessment



Inside quoFEM



UQ Algorithms

- Latin Hypercube Sampling/Monte Carlo
- Gaussian Process Regression
- Polynomial Chaos Expansion

- Probability model-based GSA (PSA)
- Principal component analysis-based PSA
- Smart Monte Carlo Method

- Local Reliability (FORM, SORM, etc.)
- Global Reliability
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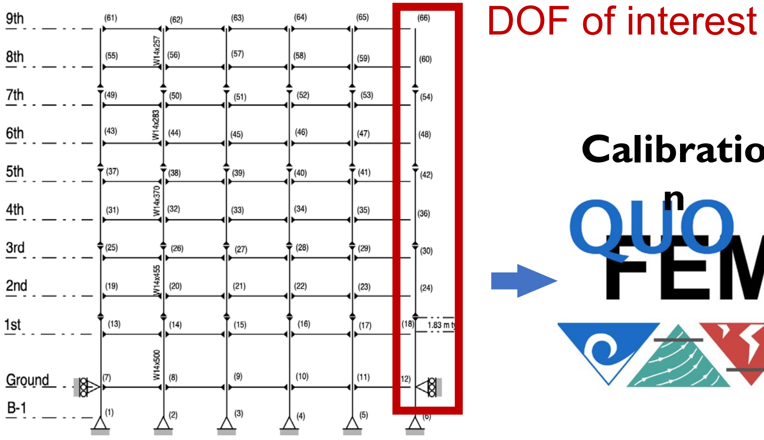
- User-provided Algorithms

Ex3. Reduced Order Modeling

High fidelity model

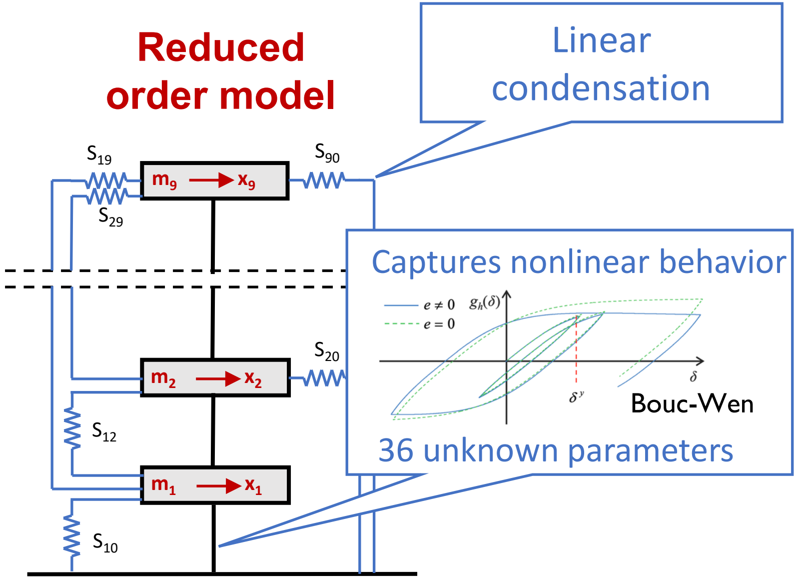


~minutes

Calibration

quoFEM

Reduced order model



~seconds

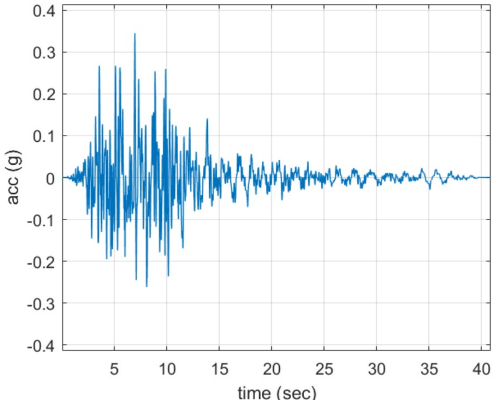
Patsialis, D., A. A. Taflanidis, and D. Vamvatsikos. "Improving the computational efficiency of seismic building-performance assessment through reduced order modeling and multi-fidelity Monte Carlo techniques." Bulletin of Earthquake Engineering (2022): 1-37.

Ex3. Reduced Order Modeling

Three ground motions used for training

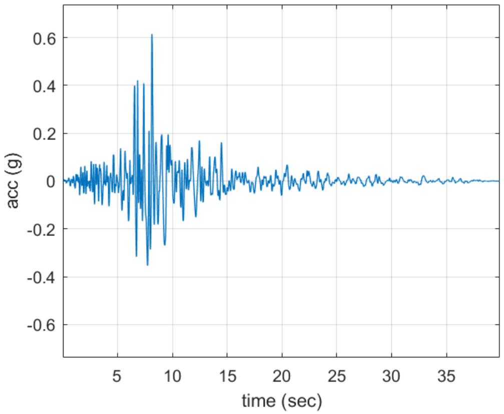
Kobe

KAKOGAWA CUE90



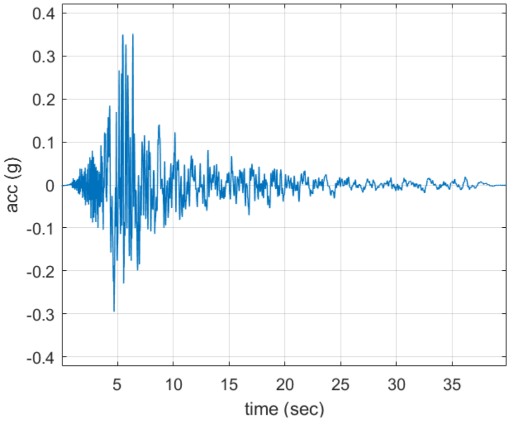
Northridge

090 CDMG Station 24278



Loma Prieta

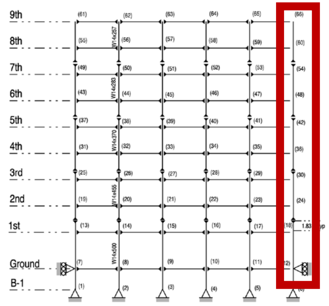
090 CDMG Station 47381



Calibration of Reduced-Order Model

Method: Transitional Markov Chain Monte Carlo (Ching and Chen, 2007)

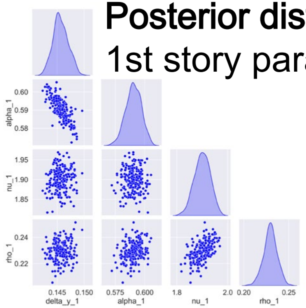
Original model



5 mins

9 story benchmark steel MRF

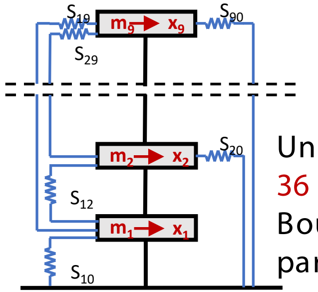
Response time history data



Posterior distribution

1st story parameters

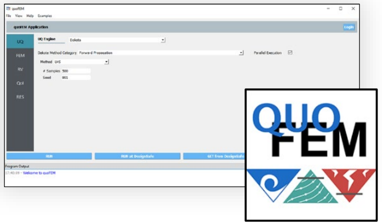
Reduced-order model



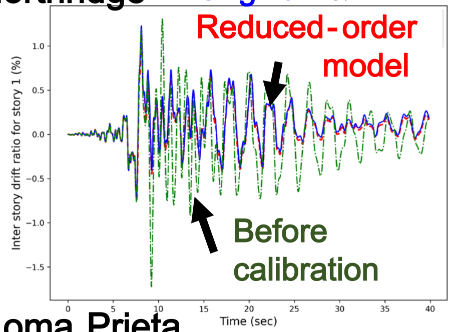
2.8 sec

Unknown 36 Bouc-wen parameters

9 DOF lumped-mass model



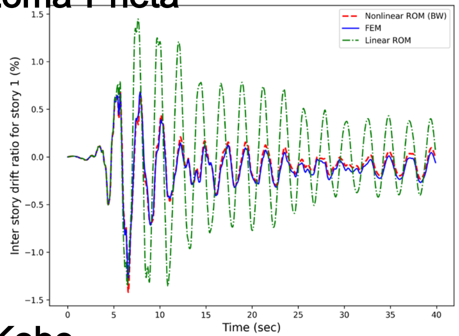
Northridge



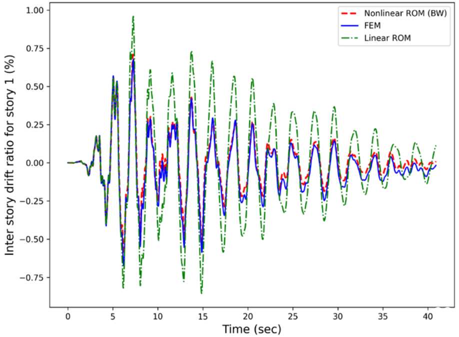
Original & Reduced-order model

Before calibration

Loma Prieta



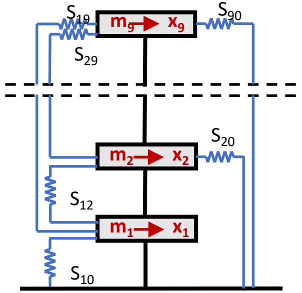
Kobe



Seismic Risk Assessment

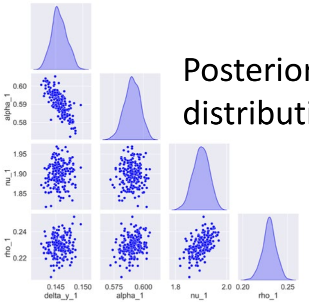
Using the reduced model and 200 artificial ground motions

Reduced-order model

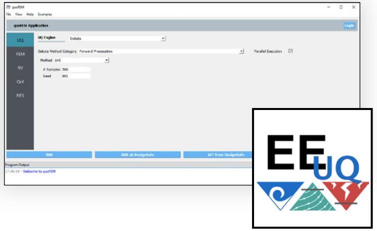


9 DOF lumped-mass model

with calibrated parameters



Posterior distribution



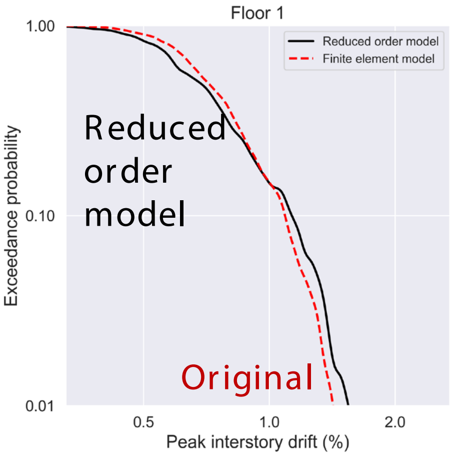
generate

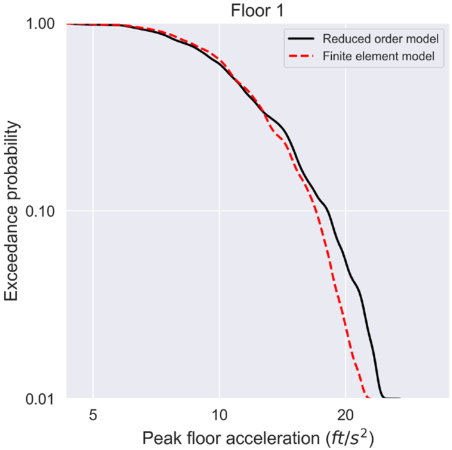
200 ground motions

$M = 7.5$ and $R = 20$ km

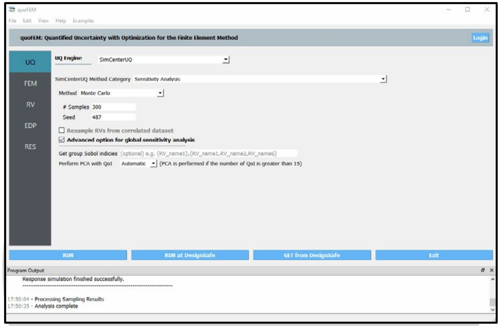
$V_{s30} = 600$ m/s

(Vlachos et al, 2018)





Benefits – SimCenter Tools for Experimental Researchers




```
Instead of                 use
      set E 205                  pset E 205
      set P 25                   pset P 25
      set Au 500                 pset Au 500
      set Ao 250                 pset Ao 250
```

1. **Moderate-to-high dimension**
2. **Efficient algorithms** for expensive models
3. **Advanced Calibration and UQ techniques**
   - Model class selection
   - Hierarchical Bayesian
   - Surrogate-enabled calibration

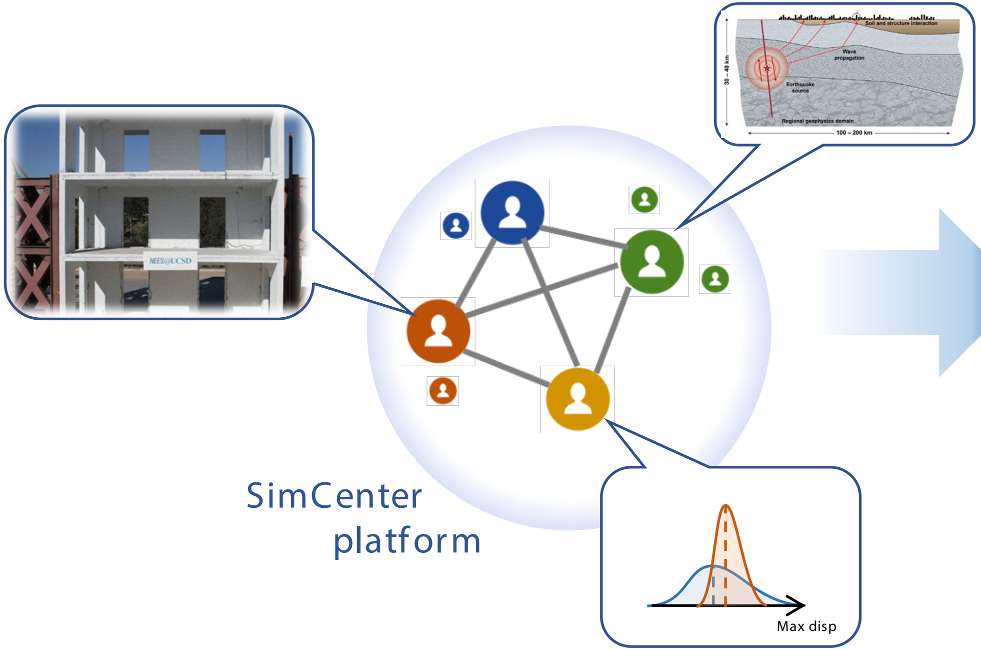
Easy-to-use user interface

Link with the DesignSafe HPC

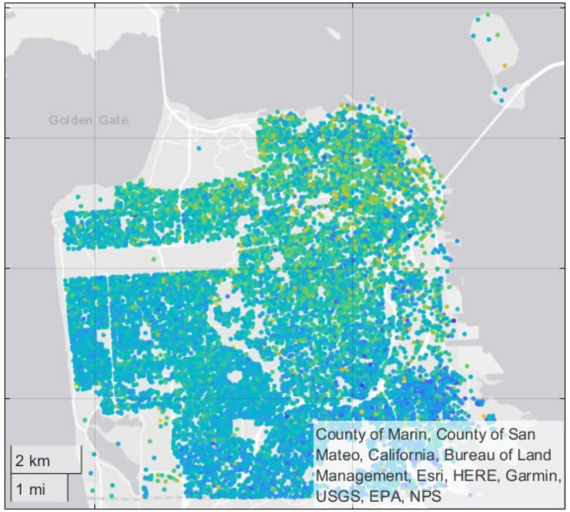
Accelerated and advanced algorithms

Summary – SimCenter Tools for Experimental Researchers

….. and broader impact through SimCenter ecosystem



Regional-scale response prediction



Thank you for your attention!